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CRITICAL EXPERIMENT ACCIDENTS - REDUX

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ABSTRACT

Much has been written regarding "process accidents" in the realm of criticality safety [1]. Indeed, great effort has been put toward analyzing the accidents for lesson-learned and toward the development of models to predict the behavior of process systems in support of safety cases an emergency response. Less effort has been levied toward the lessons-learned and modeling of critical experiment accidents. Perhaps this stems from the tenets of criticality safety: Fissionable material processes shall be determined to be subcritical under both normal and credible abnormal conditions [2].

Given the imminent startup of the Criticality Experiments Facility (CEF) at the Nevada National Security Site, an examination of critical experiment accidents for lessons-learned is prudent to ensure that the benefits of past experience is applied to CEF operations. In this paper, the history of critical experiment accidents is reviewed and lessons-learned relevant to CEF are discussed.

Key Words: Criticality Accidents

1 INTRODUCTION

The evaluation below takes the following format.

Accident descriptions are summarized from T. McLaughlin, et al; "A Review of Criticality Accidents," 2000 Revision, Los Alamos National Laboratory; LA-13638 [1]. Amplifying information on the accident summary is presented if available.

Contributing Factors: Factors contributing to the accident are identified.

Controls: Controls pertinent to each contributing factor are identified. ANSI/ANS standards are cited.

2 ACCIDENT EVALUATIONS

2.1 Los Alamos Scientific Laboratory, 18 April 1952

Jemima, cylindrical, unreflected ^{235}U metal assembly; excursion history unknown; insignificant exposures. A plot of the reciprocal multiplication versus number of plates, or total uranium, shows clearly that the system should not have been assembled with 11 plates. Nevertheless, such an assembly was attempted following a computational error made independently by two people. Contrary to operating regulations, a graph of the data had not been plotted.[1]

"The next slide shows another assembly with which we had trouble, this time arithmetic. During build-up to critical, indication that an added plate of enriched uranium would exceed critical by a certain margin was interpreted as subcritical by that same margin (naturally, the smaller number was subtracted from the larger). Too-rapid assembly (increments were available) led to a burst of 7×10^{16} fissions. Incidentally, -the light appearance of the upper support (to minimize reflection) worried us, especially for some heavier stacks than shown here. Right or wrong, we

* Footnote, if necessary, in Times New Roman font and font size 9

accepted it to get a job done rapidly. Returning to the accidental burst, a plot of data, as called for by our operating regulations, could not have been misinterpreted." [3]

2.1.1 Contributing factors

- Failure to follow "operating regulations" (procedures)
  - In particular, failure to plot the inverse multiplication versus reactivity increment.
- Failure to understand effect of core/experiment modification
  - Incorrect calculation of reactivity worth by two independent operators
  - "Too-rapid assembly," apparently based on incorrect calculations
- Underlying theme of "get the job done" (haste)

2.1.2 Controls

"Failure to follow 'operating regulations' (procedures)": ANSI/ANS-1 Section 5.1: "Requirements for conduct of operations and quality assurance may be derived from the American National Standard for Quality Assurance Program Requirements for Research Reactors, ANSI/ANS-15.8-1995."[4]

Conduct of operations requires the formal development and subsequent use of procedures to ensure deliberate, safe, secure, and compliant operations. Implementation of these requirements flows from a hierarchy of documents into the operating procedures and experiment plans utilized by the operating crew.

"Failure to understand effect of core/experiment modification"

- ANSI/ANS-1 Section 3.3: "Each new program of experiments shall be documented, independently reviewed, and approved in a manner established by management."[4]
- ANSI/ANS-14.1 Section 3.3: "Prior to the start of each experiment, an experiment plan shall be reviewed and approved in accordance with procedures approved by line management."[5]
- ANSI/ANS-1 Section 5.7: "Additions of reactivity requiring remote operation shall be guided by neutron detector response. During initial approach to criticality, reactivity shall not be added unless the effect of any preceding addition has been observed and understood."[4]

The experiment plan describes the assembly in terms of components and construction. Further, the experiment plan provides the initial configuration, reactivity increment, and estimated final configuration. This information is used in conjunction with measured data (1/M) to guide the approach to critical and final determination of the critical configuration.

2.2 Sarov (Arzamas-16), 9 April 1953

Plutonium, natural uranium reflected, assembly; single excursion; insignificant exposures. The accident on 9 April 1953 was due to an error made by an operator working alone in violation of regulations. The operator mistakenly installed 5 mm steel stops instead of the 10 mm required by the experimental plan. This caused an excursion as the assembly was brought together and resulted in a significant release of heat that melted a portion (~70 g mass) of the plutonium core.[1]

2.2.1 Contributing factors

- Failure to follow "regulations" (procedures)
  - Working alone
  - Inserted 5mm spacers vice the 10mm spacers called for by experiment plan

2.2.2 Controls

The same controls described in 2.1.2 above apply here in addition to those below.

- ANSI/ANS-1 Section 3.5: "At least two persons who have qualifications approved by management shall be present while a critical experiment is being performed."[4]
- ANSI/ANS-14.1 Section 3.5: "At least two members of the reactor operating staff, one of

whom is a reactor supervisor, shall be present in the reactor facility during operation of the reactor, and one of the two shall be present at the control console at all times during operation of the reactor."[5]

2.3 Los Alamos Scientific Laboratory, 3 February 1954, 12 February 1957

Lady Godiva reactor; bare ^{235}U sphere; control rod incorrectly operated; single excursion; insignificant exposures. Because the only source of neutrons was spontaneous fission, it was customary to assemble to an excess reactivity of about 70 ¢ to generate sufficient neutrons to determine the settings for delayed criticality in a reasonable time. This accidental excursion was caused, apparently, because additional reactivity was inserted by error after assembly to 70 ¢, but before a fission chain started. [1]

"Apparently, the control rods had been run to their wrong extreme, i.e., to the position of maximum reactivity, before the booster was inserted. An interlock to prevent this had been omitted in the course of remodeling the assembly and, contrary to regulation, only one crew member was in the control room during the operation that led to the incident." [6]

"In this incident, the operator, who was alone in the control room, inserted the control rods too far before firing the burst rod. The nonstandard operational sequence, even though it had been followed successfully many times previously, was the immediate cause of this incident. Other contributing factors were the solo operation of the reactor and the marginal excess reactivity available." [7]

Lady Godiva reactor; bare ^{235}U sphere; added reflection; single excursion; insignificant exposures. The second accidental excursion occurred during preparations for an experiment in which Godiva was to provide a pulse of fast neutrons. Again, the burst occurred during assembly to establish, in this case, a fiducial point at about 80 ¢ excess reactivity. Control rods were to be adjusted on the basis of this period. The extra reactivity is thought to have been contributed by a large mass of graphite and polyethylene that was to be irradiated. This mass had just been moved close to Godiva, and either the change in reflection was underestimated or the material slumped further toward Godiva. [1]

"Both accidents occurred during preliminaries that were designed to establish the reactivity slightly below prompt critical. In the first case, a 100 ¢ booster, inserted with control rod in the position of maximum instead of minimum reactivity, led to a burst of 6×10^{16} fissions, The burst of 1.2×10^{17} fissions that retired the old Godiva apparently resulted from a shift of a nearby setup, that was to be irradiated." [3]

"... a large moderating experiment was being irradiated near an early Godiva-type reactor. At the same time, a second experiment was being irradiated in the burst-rod cavity. The burst rod had been removed, and the safety block as used to initiate the power transients. Although somewhat involved, this procedure was quite satisfactory until the large external experiment was modified. In the modification both the configuration of the moderator and its distance from the reactor were changed—not obviously but, as it happened, significantly. When operation was resumed, the control rods were driven to their previously determined initial positions. Insertion of the safety block for the period calibration initiated an excursion with a 12-times-normal yield, and the reactor was badly damaged. The failure of this incident was not an unsafe operating procedure; it was a failure of the operations crew to appreciate the ease with which a small change in an experiment can produce a significant reactivity perturbation."[7]

2.3.1 Contributing factors

- Failure to follow procedure (First accident)
  - Delayed Critical not properly established
  - Only one operator in control room

- Failure to understand effect of core/experiment modification (Second accident)
  - No approach to critical to determine change in experiment worth
- Underlying theme of "get the job done." (Both accidents)

2.3.2 Controls

"Failure to follow procedures": The same controls described in 2.1.2 above apply here in addition to those below.

- ANSI/ANS-14.1 Section 7.10: "The pulse production cycle shall consist of (1) a reference reactivity check at delayed critical or by means of a controlled positive period; (2) adjustment of the control and/or pulse element positions, taking into account the reactor fuel temperature and the effects of the experimental arrangement on the reactivity of the pulse element so that actuation of the pulse element will give the desired reactivity. This latter adjustment may be part of a procedure to determine the reactivity of the pulse element using a subprompt critical positive period measurement; …"[5]

"Failure to understand effect of core/experiment modification"

- ANSI/ANS-14.1 Section 7.5: "The effects of reactivity changes shall be observed and be consistent with reactor operating staff expectations. Unless a scram is warranted, deviations shall be evaluated before proceeding further.[5]
- ANSI/ANS-14.1 Section 7.7: "Consideration of the influence of an experiment on reactivity and the calibration of control elements shall be guided by prior experiment information or calculation, or both."[5]

2.4 Los Alamos Scientific Laboratory, 3 July 1956

Honeycomb critical assembly; U(93) metal foils moderated with graphite; single excursion; insignificant exposures. The stacking on 3 July 1956 consisted of 58 kg of enriched (93% ^{235}U) uranium in the form of 2 and 5 mil foils arranged between slabs of graphite with some beryllium reflector surrounding the core. At the time, some changes had been made in the reflector and graphite moderator, and criticality was being approached too rapidly for routine measurements. While the cart was moving at about 0.2 inch per second, the system became prompt critical, a burst occurred, and the scram system retracted beryllium control rods (reducing reactivity) and reversed the motion of the cart.[1] "Too large a change in the core, and incautious assembly led to the burst of 3×10^{16} fissions (the system became critical beyond the range of a slow-down)." [3]

2.4.1 Contributing factors

- Failure to understand effect of core/experiment modification
  - No estimate of reactivity worth of the changes
  - No approach to critical to determine change in experiment worth
- Underlying theme of "get the job done."

2.4.2 Controls

The same controls described in 2.1.2 above apply here.

2.5 Los Alamos Scientific Laboratory, 17 June 1960

^{235}U metal, graphite reflected, assembly; single excursion; insignificant exposures. The critical parameters of highly enriched (93% ^{235}U) uranium metal cylinders in thick graphite (about 9 inches) and near infinite water reflectors were being investigated. In the experiment of interest, an approximate 48 kg uranium annulus was built up on a cylinder of graphite that, in turn, rested on a hydraulic lift device. This annulus was raised by remote control into a reflector of graphite resting on a stationary steel platform. The system became critical before complete assembly and was scrammed both manually and automatically at about 1 inch from closure.[1]

2.5.1 Contributing factors

- Failure to understand effect of core/experiment modification
  - No approach to critical to determine change in experiment worth

2.5.2 Controls

The same controls described in 2.1.2 above apply here.

2.6 Oak Ridge National Laboratory, 10 November 1961

^{235}U metal, paraffin reflected, assembly; single excursion; insignificant exposures. This power transient in about 75 kg of highly enriched (about 93% ^{235}U) uranium metal reflected with paraffin took place when one portion on a vertical lift machine was approaching the other stationary portion. The experiment was the last of a series during which uranium or paraffin had been added by increments to change the reactivity of the complete system; all previous experiments had been subcritical when fully assembled. In this case, the system became supercritical while the lift was in motion, leading to a yield of between 10^{15} and 10^{16} fissions.[1]

"The occurrence was the result of errors in judgement by those performing the experiment."[8]

2.6.1 Contributing factors

- Failure to understand effect of core/experiment modification
  - No approach to critical to determine change in experiment worth

2.6.2 Controls

The same controls described in 2.1.2 above apply here.

2.7 Los Alamos Scientific Laboratory, 11 December 1962

Zepo critical assembly; ^{235}U foils, graphite moderated; single excursion; insignificant exposures. The critical assembly consisted of a large cylindrical enriched uranium–graphite core on a lift device and a stationary platform holding a reflector of graphite and beryllium into which the core was raised. The experiment was concerned with measurements of the axial fission distribution, which was perturbed from its normal value by an end reflector of layers of graphite and polyethylene. For this reason, some fresh ^{235}U foils had been placed in the assembly to obtain a reasonably precise value of the fission energy release. The crew assumed the assembly had been run and checked the previous day; however, this was not the case. The system became critical with the core in motion upward.[1]

2.7.1 Contributing factors

- Failure to understand effect of core/experiment modification
  - Failure to understand core configuration prior to operation
  - No approach to critical to determine change in experiment worth

2.7.2 Controls

The same controls described in 2.1.2 above apply here.

2.8 Sarov (Arzamas-16), 11 March 1963

Plutonium, lithium deuteride reflected assembly; inadvertent closure; single excursion; two serious exposures. On 9 March 1963, the MSKS chief and operations engineer constructed the assembly on MSKS and conducted approach to critical experiments without first performing the required experiments on FKBN-1. On 11 March 1963, the facility chief and the operations engineer proceeded with pre-experiment operations with the assembly pieces still in place. The experimentalists attempted to make adjustments to the machinery of MSKS using unauthorized attachments in violation of the operating procedures. As they worked on MSKS adjusting the electromechanical lift mechanism, an excursion occurred. The automatic scram system did not activate because the detectors to which it was tied were not operating. The accident was the result of gross violations of the MSKS operating procedures by the facility chief and operations engineer. The excursion was due to the inadvertent closure of the assembly by the experimentalists.[1]

2.8.1 Contributing factors

- Failure to follow procedure
  - Construction of new assembly on MSKS without prior demonstration on FKBN
  - Unauthorized adjustments made to machine with material in place
  - Detectors for automatic scram system not operating
- Failure to understand effect of core/experiment modification
  - No approach to critical to determine change in experiment worth

2.8.2 Controls

There is no analog to this accident in CEF operations. However, the operation described may be compared to the transition from local operations to remote operations at CEF.

"Failure to follow procedure": The same controls described in 2.1.2 above apply here in addition to those below.

- ANSI/ANS-1 Section 3.9: "Manual operations that result in reactivity additions to a critical assembly should be limited to a predicted k_{eff} of 0.9 (a neutron multiplication of 10) for unknown configurations. Manual operations of known configurations with adequate control and analysis should use a predicted k_{eff} not to exceed 0.95 (a neutron multiplication of 20). When available, measured multiplication values shall take precedence over computed values."[4]
- ANSI/ANS-1 Section 3.10: "Additions of reactivity to a critical assembly beyond those permitted by 3.9 shall be made by remote operation. Such additions shall be continuously adjustable, except when the resulting reactivity is known with an accuracy such that safety is not compromised."[4]
- ANSI/ANS-1 Section 5.3: "The satisfactory performance of newly installed or altered control equipment or safety devices shall be established before any attempt to achieve criticality."[4]
- ANSI/ANS-1 Section 5.6: "The proper functioning of each required safety device shall be established before starting operations each day that a critical experiment is to be initiated. In the course of these test's or early in each day's operation, the response of each required detector system to a change in neutron or gamma-ray intensity shall be observed."[4]

"Failure to understand effect of core/experiment modification": The same controls described in 2.1.2 above apply here.

2.9 Lawrence Livermore Laboratory, 26 March 1963

^{235}U metal, beryllium reflected, assembly; single excursion; insignificant exposures. The critical assembly consisted of concentric cylinders of highly enriched uranium metal surrounded by a beryllium reflector. The total enriched uranium mass of 47 kg was divided into two parts with the central core on a lift device and the larger diameter rings with the reflector on a fixed platform. The approach to criticality was to be achieved by lifting the core in a series of steps into the reflected annulus. This step wise assembly procedure was successfully followed for seven multiplication measurements. After the eighth apparently normal assembly, the system suddenly became highly supercritical. The accident is believed to have been caused by the central cylinder of metal on the lift being very slightly off center. When it was lifted into the fixed half, one or more of the metal rings were carried upward. Following the eighth assembly, the system adjusted itself and the rings settled properly around the central core, abruptly increasing the reactivity.[1]

"The cause of the excursion is believed to be directly attributable to mechanical failure. The ram may have been slightly off center with respect to the remainder of the assembly, and, as it was raised, the ram carried the innermost cylinder upwards. A small disturbance realigned the cylinder, and it slipped down over the ram, changing the geometry sufficiently to allow a prompt criticality to occur."[9]

2.9.1 Contributing factors

- Design Flaw

2.9.2 Controls

As noted in 2.1.2, ANSI/ANS-1 requires that experiments be documented, independently reviewed, and approved. Implementation occurs within the *Experiment Plan Preparation Procedure*, which requires that experiment plans be reviewed through the Criticality Experiments Safety Committee. This independent, objective review is designed to expose design pitfalls exemplified by this accident.

2.10 White Sands Missile Range, 28 May 1965

Unreflected uranium–molybdenum metal fast burst reactor; single excursion; insignificant exposures. The assembly was held together by three metal bolts. Initially, the bolts were stainless steel, but just prior to the accident they were replaced by bolts composed of the uranium–molybdenum alloy, and re–calibration of the reactivity worth of various components was underway. The new worth of the control rods, burst rod, minor components, and the first inch withdrawal of the safety block had been measured. Further calibration of the safety block seemed to require higher neutron flux than that given by a polonium–beryllium neutron source. To obtain a power of about 1 watt, an interlock was bypassed and the safety block was set into motion inward, approaching a state thought to be known. The excursion took place as the safety block neared the one–half inch position.[1]

"A point in the calibration procedure was reached at which the reactor was near critical with the burst rod and all control rods fully inserted; the neutron level was so low, however, that erratic instrument response made it uncertain whether or not the reactor was actually critical. Departing from the written procedure, the facility supervisor decided to return the reactor to an earlier configuration in which the reactor could be made supercritical. For this procedure it was necessary to scram the reactor. The scrams were reset as soon as the safety-block slow-drive mechanism reached its fully retracted position, but at that time, the control rods had moved only 0.7 in. (worth a total, for both rods, of about 20¢) from their fully inserted positions. The burst rod remained clamped in its most reactive position. Among the interlocks that had been bypassed was one requiring the control and burst rods to be withdrawn before the safety block could be inserted. Starting at that condition, then, the facility supervisor (with the passive concurrence of the other members of the operating crew) ordered the pneumatic safety-block insertion mechanism to be actuated. The reactor assembled rapidly toward a configuration that potentially could have reached a reactivity of 40¢ above prompt critical, but preinitiation at about 15¢ limited the fission yield to approximately 1.5×10^{17}."[7]

"Again, the departure from established operating procedures was the direct cause of the incident. Although the seriousness of the facility supervisor's judgement cannot be minimized, a significant contributing factor was the failure of the two operating crew members to provide a human interlock against such errors. This incident is similar to the first [Godiva 3FEB54] in the sense that, effectively, there was only one operator. Obviously, little is gained by requiring operational crews of more than one person unless each person carries out his duties with a full awareness of his responsibilities."[7]

2.10.1 Contributing factors

- Failure to follow procedure - "On-the-spot" procedure change
- Failure to understand effect of core/experiment modification - Control rods not fully withdrawn when scram was reset
- Underlying theme of "get the job done"

2.10.2 Controls

The same controls described in 2.1.2 above apply here.

2.11 Chelyabinsk-70, 5 April 1968

U(90) metal, natural uranium reflected, assembly; single excursion, two fatalities. Two specialists present for the daytime assembly decided to continue working into the evening in order to complete a second assembly. The evening assembly was to be a repeat of the daytime assembly with one variation—a solid polyethylene sphere was to be inserted into and fill the cavity of the core which was void for the daytime assembly. Using a hand-held controller panel, the senior specialist operated an overhead tackle to lower the upper half of the reflector to make contact with the core. The accident occurred as the upper half of the reflector was being lowered onto the core and was about to make contact with it. The senior specialist made an error of judgment when he expected the polyethylene sphere to have a small effect on system reactivity.[1]

The investigation also established that in addition to the error in judgment, the specialist violated several operational procedures. For the evening assembly, the lower half of the uranium reflector was not positioned 20 mm above its lower stop as required to ensure an adequate margin of criticality safety for the assembly process. The failure to reposition the lower reflector following the daytime assembly was identified as the primary cause of the accident. The instrument system designed to be sensitive enough to alert the specialist that system multiplication was rapidly increasing as they lowered the upper reflector half was not operating. This system had been switched off following the daytime assembly and not switched back on for the evening assembly. A third specialist was required to be present in the control room, but the control room was unmanned. The assembly required the presence of a health physicist. The health physicist was not present because he was not notified of the evening assembly.[1]

2.11.1 Contributing factors

- Failure to follow procedure
  - Failure to reposition lower reflector following the daytime assembly
  - Instrument system used to monitor multiplication not switched on
  - Required crewmembers not present
- Failure to understand the effect of core/experiment modification
  - No approach to critical to determine change in experiment worth
- Underlying theme of "get the job done."

2.11.2 Controls

"Failure to follow procedures": Conduct of operations and crew member requirements addressed earlier apply here. Proper configuration of the assembly and associated safety systems is implemented in the machine procedures.

"Failure to understand effect of core/experiment modification": The same controls described in 2.1.2 above apply here.

2.12 Aberdeen Proving Ground, 6 September 1968

Uranium–molybdenum metal fast burst reactor; single excursion; insignificant exposures. During pre-operational testing, several minor variations in the reactor configuration were studied in a program to optimize performance. During this testing, an unexpectedly large burst (6.09×10^{17} fissions) occurred. Post accident analysis indicates that the extra reactivity resulted from a reactor configuration such that the burst rod passed through a reactivity maximum before seating. This condition had not been recognized; apparently on previous operations the burst rod had reached its seated position before the arrival of an initiating neutron.[1]

"The only incident that can be attributed unambiguously to a design deficiency was the one caused by an actuator moving the burst rod through a position of maximum reactivity. Therefore, while the burst-rod worth as measured between its two end positions was as specified, the maximum worth was several cents higher. In this incident initiation occurred when the burst rod was near its position of maximum worth and the reactivity was some 10¢ higher than intended."[7]

2.12.1 Contributing factors

- Design flaw - Pulse element passed through maximum reactivity prior to seating

2.12.2 Controls

- ANSI/ANS-14.1 Section 5.7: "The pulse element should be designed so that it reaches its maximum reactivity value at the limit of its travel."[5] Godiva-IV design precludes the burst rod from passing through a reactivity maximum.

2.13 Kurchatov Institute, 15 February 1971

$U(20)O_2$ fuel rod, iron and beryllium reflected, assembly; multiple excursions; two serious exposures. The second stage of the experiment, according to the plan, began with the beryllium reflector in place because it was in place at the end of the first stage. Based on results of the comparison between beryllium and iron reflectors for the first configuration, the supervisor of the experimental team determined that substituting iron for beryllium would not result in any considerable increase in reactivity. Therefore, additional calculations were not performed. The next morning, the supervisor entered the facility control room and without waiting for the arrival of the control console operator and the supervising physicist, switched on the pump, and began adding water to the critical assembly tank. The control equipment was switched on, but the neutron source had not been placed in the critical assembly, and the control rods were not actuated. Later assessments showed that about 50 pulses occurred. [1]

It was incorrectly judged that the reactivity worth of the beryllium reflector was essentially the same as the iron reflector. Serious violations of SF-7 operating requirements occurred. Action that could change the core reactivity should have been considered an experiment. The addition of water was an obvious change to the core reactivity and should not have been initiated without a full operating crew. Before initiating the experiment (adding water) all control equipment should have been tested, the neutron source should have been introduced into the core, and the safety rods should have been inserted. Any reactivity addition should have been done step–by–step. The parameter 1/M should have been plotted and extrapolated to the critical value after each step.[1]

2.13.1 Contributing factors

- Failure to follow procedure
  - Any action that could change reactivity considered an experiment, required full crew
  - Required crewmembers not present
  - Prior to water addition, startup testing was required
  - Any reactivity addition required 1/M with subsequent extrapolation to critical
- Failure to understand effect of core/experiment modification
  - No calculations performed for configuration
    - Incorrect assumptions made based on first experiments with different configuration
  - No approach to critical to determine change in experiment worth
- Underlying theme of "get the job done"

2.13.2 Controls

"Failure to follow procedures": Conduct of operations, crew member and approach to critical requirements addressed earlier apply here. Proper configuration of the assembly and associated safety systems is implemented in the machine procedures and experiment plans.

"Failure to understand effect of core/experiment modification": The same controls described in 2.1.2 above apply here.

2.14 Kurchatov Institute, 26 May 1971

U(90) fuel rod, water reflected, assembly; single excursion; two fatalities; two serious exposures. The assembly consisted of a 20 mm thick Plexiglas base plate which supported the weight of a lattice of fuel rods, and 2 mm thick aluminum plates used to hold the end of the rods in position. The construction was quite delicate and fragile. In the final experiment, the critical number of fuel rods with the smallest pitch (7.2 mm) was measured. This number was 1,790 and exceeded the minimum critical number of rods for an optimum pitch by approximately 7 times. After the experiment was finished, the supervisor of the experimental team ordered the insertion of all control and emergency protection rods and the neutron source was removed from the core. The supervisor then ordered the water be removed through the fast dumping (emergency) valve. The water from the critical assembly tank could have been drained through the slow dumping valve in 15 to 20 minutes or through the fast dumping valve in 20 to 30 seconds. After the previous experiments, the water had been drained through the slow dumping valve. The plexiglas support plate almost completely covered the tank section, and the size of the gap between the plate edge and tank wall was less than the size of the fast dumping valve outlet. For this reason, upon initiating the fast dumping operation, the Plexiglas base plate sagged and the fuel rods fell out of the upper lattice plate. The fuel rods separated into a fan shaped array in which the pitch between the rods came close to optimum and the lattice went highly supercritical.[1]

The construction of the critical assembly was the main cause of the accident. No calculations were performed for the components of the system and the construction as a whole. Improper and hasty actions by personnel during the final stage of the experiment also contributed to the cause of the accident.[1]

2.14.1 Contributing factors

- Failure to follow procedure
  - Emergency dump ordered instead of the slow dump used previously
- Design flaw
  - "Flimsy" core support plate (Plexiglas)
  - Size of gap between support plat edge and tank wall created smaller surface area than the cross section of the emergency dump valve
- Underlying theme of "get the job done."

2.14.2 Controls

"Failure to follow procedures": The same controls described in 1.2.2 above apply here.

"Design Flaw": As noted in 2.1.2, ANSI/ANS-1 requires that experiments be documented, independently reviewed, and approved. Experiment plans are reviewed through the Criticality Experiments Safety Committee. This independent, objective review is designed to expose design pitfalls exemplified by this accident.

2.15 Sarov (Arzamas-16), 17 June 1997

U(90) metal, copper reflected, assembly; multiple excursions; one fatality. On 17 June 1997, an experimenter working alone and without having completed the proper paper work (both violations of safety requirements), was constructing an experimental assembly consisting of a core of uranium, U(90) reflected by copper. He had taken the dimensions for all of the system components from the original 1972 logbook. However, when he copied down the inside and outside dimensions of the copper reflector (167 and 205 mm, respectively) he incorrectly recorded the outside dimension as 265 mm. Using this incorrect information, the experimenter had completed the construction of the lower half of the assembly on the table. As he went to position the first upper copper hemishell (with an inside and outside diameters of167 mm and 183 mm, respectively) into place it dropped onto the bottom assembly. This led to the initial prompt critical spike and the ~6.5 day excursion. The automatic scram system activated and dropped the table to its down position but otherwise had no effect on the supercritical assembly.[1]

2.15.1 Contributing factors

- Failure to follow procedure
  - "Proper paperwork" not completed
  - Working alone
- Failure to understand effect of core/experiment modification
  - Transcribed wrong dimensions from logbook (265mm vice 205mm)
- Underlying theme of "get the job done"
- Documentation error

2.15.2 Controls

"Failure to follow procedures": Conduct of operations, crew member and approach to critical requirements addressed earlier apply here. Proper configuration of the assembly and associated safety systems is implemented in the machine procedures and experiment plans.

"Failure to understand effect of core/experiment modification": The same controls described in 2.1.2 above apply here.

3 CONCLUSIONS

Based on a review of the available literature, contributing factors to the accidents were identified. Table I below summarizes the contributing factors for each evaluated accident.

Table I. Summary of contributing factors

Incident Number / Contributing Factors	1	2	3*	4	5	6	7	8	9	10*	11	12*	13	14	15	Total
Failure to understand effect of core/experiment modification	x		x	x	x	x	x	x		x	x		x		x	11
Failure to follow procedure	x	x	x					x		x	x		x	x	x	9
Get the job done (haste)	x		x	x						x	x		x	x	x	8
Working alone/required crew not present		x	x								x		x		x	5
Design flaw									x			x		x		3
Documentation error															x	1
Total	3	2	4	2	1	1	1	2	1	3	4	1	4	3	4	
Exposure/Fatality								E			F		E	F	F	

*Fast Burst Reactor

As can be seen, the major contributor to the accidents was a failure to understand the effects of modifications made to the core and/or experiment. Failure to follow procedures and hastily executed operations were similar in magnitude. Two of the accidents were directly attributable to design flaws. Three accidents resulted in 5 fatalities. Each of those accidents involved multiple contributing factors. Of note, 3 of the 5 fatalities resulted from operations without the required crew complement present. All fatalities were a result of hands-on or collocated operations.

None of these accidents resulted from a cause that does not have a control identified in the basis for CEF operations. In other words, implementation of the CEF safety basis and operating procedures effectively precludes the accidents.

Three fundamental conclusions are drawn from this evaluation. Develop appropriate procedures (including experiment plans). Execute those procedures as written (conduct of operations). Crew members must be certified by line management as knowledgeable and experienced in the methods and requirements for operation of the assemblies.

Presentation in this format identifies discrete controls for each identified contributing factor. However, this method does not present the integral suite of controls employed by CEF operations. Thus, this format cannot effectively communicate the defense in depth implemented as a consequence of adherence to ANSI/ANS Standards. A thorough understanding of the CEF Authorization Basis and operating philosophy is necessary to fully appreciate the depth, breadth, and effectiveness of controls applied to CEF operations.

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